Chapter – III

CHAPTER 3

DESIGN, DEVELOPMENT AND TESTING OF PROTOTYPE SIX PHASE INDUCTION MOTOR

3.1. INTRODUCTION

This chapter focuses on complete design, development and testing of prototype six phase induction motor. The design of six phase induction motor is done as per three phase induction motor initially. The problems faced with existing three phase motor specifications are discussed in detail. Actual design and development of six phase induction motor at a manufacturing unit is discussed in detail.

As per the area of application, i.e. high power-high current, multiphase motors are of very high rating. So to design a techno economical motor, moderate and economical size which can very well show the characteristics of multiphase motor is chosen. Thus a 3 HP, 4 pole, 200 V, six phase induction motor specifications are calculated for prototype six phase motor. As per novel calculations, reasonable size of stampings is selected which also eliminated the need of third harmonic current injection. How torque improvement is achieved without any harmonic injection or current sensor is proved at the end.

3.2 ACTUAL DESIGN OF PROTOTYPE SIX PHASE INDUCTION MOTOR:

To begin with, an m-phase symmetrical induction machine, such that the spatial displacement between any two consecutive stator phases equals $\alpha = 2\pi/m$, is considered. Stator winding is treated as m–phase and it is assumed that the windings are sinusoidally distributed, so that all higher spatial harmonics of the magneto-motive force can be neglected. The phase number m can be either odd or even. When the number of phases is six, i.e. m = 6, there are two, three phase windings. The two, three phase windings are displaced by 60^0 in symmetrical design but there is a problem of magnetic circulating currents. So asymmetrical design is implemented in which two, three phase windings are displaced by 30^0, which eliminates ($6n \pm 1$) order harmonics, where n = 1,3,5.......... [1].

A six phase machine can be easily constructed by splitting the 60^0 phase belt into two portions each spanning 30^0.The winding distribution factor increases from 0.965 for three phase to 1.0 for six phase for split phase belt connection.[20] A true six phase that retains the same winding pitch and distribution factor is shown in the table below. The last column represents six phase asymmetrical winding which is implemented for prototype motor.

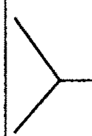
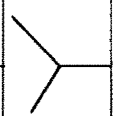
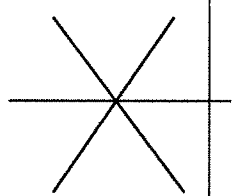
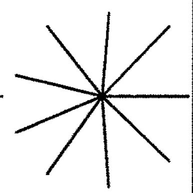
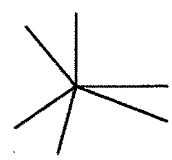
Phase belt angle (degrees)	120	60	60	40	30
No. Of phase belt per pole	1.5	3	3	4.5	6
Number of stator terminals	3	3	6	9	6
Connection name	THREE PHASE	SEMI SIX PHASE	SIX PHASE SYMMETRICAL	NINE PHASE SYMMETRICAL	SIX PHASE ASYMMETRICAL
Schematic diagram of star connection & voltage phasor diagram					

Table 3.1:- Multiphase Winding configuration

The six-phase machine uses the same magnetic frame with the baseline machine. So initially the stator dimensions, stator size, rotor size etc. were kept same as 3 phase, 3 HP induction motor. And the same stator is rewound for making six phase.

Stator design depends upon number of stator slots. General expression for number of stator slots is given by,

$$S_s = m/2.p\ [2+K]\ \text{Slots} \quad [3.1]$$

Where, S_s = No. of Stator Slots

m = No. of machine phases

p = No. of machine poles

K = 0,1,2.....

For Symmetrical ac winding: K = 0,2,4.....

For Asymmetrical ac winding: K = 1,3,5....

In this case no. of poles = 4, so putting the values of m, p, K in equation [3.1] we get,

$$S_s = (6/2).4[2+1] = 36 \quad [3.2]$$

Thus it is a 4-pole machine with 36 stator slots. In order to keep the leakage distribution balanced, the phases are displaced among the two stator layers. The six-phases are constructed such that one three-phase group is displaced from the other one by 30 electrical degrees.

Thus it is an asymmetrical six phase machine

where;

$$\theta m = 2.\ \theta e / p \quad [3.3]$$

$$\theta m = 2\ .30° / 4 = 15° \text{ mechanical} \quad [3.4]$$

$$\text{Slot pitch} = 360° / 36 = 10° \text{ mechanical} \quad [3.5]$$

Hence, the 30 electrical degrees displacement corresponds to 15°/10° = 1.5 slots.

It is not possible to implement such a configuration and an approximation has to be used. This is done as shown below:

One of the three-phase groups has the same structure of the baseline machine with half of the circuits and winding distributed in 3 slots per pole per phase ($q_A = 3$)

The second group is distributed into 4 slots per pole per phase ($q_X = 4$) but keeping the same number of conductors per pole per phase.

Initially the same dimensions as per 3 phase, 3 HP, induction motor have been used. And stator is divided into two parts and winding is carried out as discussed above.

Prototype six phase induction motor is developed in such a way that, first three phase set say, "ABC" has two pole pitches viz. 9 for outer layer and 7 for inner layer. While the second three phase set say "XYZ" has two pole pitches viz.8 for outer layer and 6 for inner layer. The number of poles is kept same for both the windings. Also wire gauge and number of turns are same for both the windings. The neutrals of two three phase sets are kept open. The motor is star connected.

The initial design parameters, which are implemented for developing a prototype 3 HP, 4 pole 3 phase squirrel cage induction motor, are having 36 stator slots with stator bore diameter 105 mm and 33 rotor slots.

There are 96 conductors per slot of 24 SWG with number of turns equal to 144 with insulation class B (130° C).

The specifications are listed below:

Stator Dimensions:-	
● **Number of slots**	**36**
● **Inner diameter**	**105mm**
● **Stack length**	**110mm**
Rotor Dimensions:-	
● **Number of slots**	**33**
● **Outer diameter**	**105mm**
● **Inner diameter**	**33.5mm**
● **Stack length**	**110mm**
Winding Details:-	
● **conductors per slot**	**96**
● **No. of turns**	**144**
● **Conductor Size**	**24 SWG**
● **Insulation**	**Class B**

3.3 PROBLEMS FACED IN DEVELOPMENT OF MOTOR

Motor developed with these parameters (used same dimensions as per three phase motor) have very compact winding.

Initially two three phase sets of developed motor are tested alternatively one by one from three phase supply and following points are noted:

1. Over heating is experienced even under no load condition.
2. Over heating has also lead to failure of insulation.
3. With these specifications, when one of the three phase sets was fed with three phase AC supply, the motor started vibrating..
4. Also because of high input voltage i.e. 415 V to one of the three phase sets say ABC, after sometime motor started burning.
5. Also there was a problem of Body earth because of complicated winding and proper insulation not done at the time of actual winding.

3.3.1 Solution to the Problem:-

To overcome above said problems following steps are taken:

1. Over heating is caused due to I^2R losses. If the heat dissipating area can be increased and at the same time number of conductors and conductor size changed, it will

affect the current. Thus the frame size of the motor is increased as per the calculations shown in next section. Also number of conductors is increased as per the slot. And conductor size is changed from 24 SWG to 22 SWG.

2. To avoid insulation failure due to overheating, the insulation class is changed from class B (130^0) to class F (155^0).
3. Vibration is experienced because of high torque. To overcome vibration, frame size is increased. This increases the mechanical strength of motor and eliminates third harmonic current injection.
4. The motor voltage is increased gradually up to 200 Volts, to overcome burning problem.
5. As frame size is increased slot area is increased thus there is no compact winding.

3.4 RE DEVELOPMENT WITH NEW SPECIFICATIONS: (Novel Design)

The practical problems faced at the time of actual development of prototype were overcome by using next higher standard stator stamping. As per the calculations for six phase motor the main dimensions are not same as three phases. But the stator slots, pole pitches are kept same.

3.4.1 Calculations:

To design main dimensions of 3 HP (2.238 KW), 200 Volts, 6phase, 4 pole induction motor (assuming efficiency η= 85%, power factor $\cos\Phi = 0.8$ lagging

Q = Output in KW / η x $\cos\Phi$ [3.6]

$Q = 2.238 / 0.85 \times 0.8 = 3.3$ KVA [3.7]

Also $Q = C_0 D^2 L n_s$ [3.8]

(Appendix-I)

And $C_0 = 11\ B_{av}\ ac\ Kw\ 10^{-3}$ [3.9]

(Appendix-I)

Kw = Window space factor for 6 phase = 1

Assuming Specific magnetic loadings B_{av} = 0.65 wb/m^2 , Specific electric loading, ac = 12000 Ampere conductors

$C_0 = 11 \times 0.65 \times 12000 \times 1 \times 10^{-3} = 85.8$ [3.10]

Putting the value of C_0 from [3.10] in [3.8]

We get, D = 0.124 m = 124 mm [3.11]

Taking overall good design condition, i.e. $L / \Gamma = 1$ [3.12]

Where, Γ = pole pitch = $\pi D / p$ [3.13]

Thus L = 0.102 m = 102 mm [3.14]

Similarly turns per phase,

$T_{ph} = E_{ph} / 4.44\ f\varphi\ Kw = 312$ [3.15]

[Appendix-I]

Total conductors = $Z_{ss} = 2mT_{ph}$ [3.16]

Stator slots S_s =36, no. of phases m =6

Thus Total conductors = 3744

Conductors per slot $Z_s = Z_{ss} / S_s = 3744 / 36 = 104$ [3.17]

The next higher standard dimension stamping available at the manufacturing unit near to the calculated value are selected. Standard Stator bore diameter available is 125 mm, nearest to the calculated value 124 mm. And stack length as per standard is selected as 100mm nearest to 102 mm.

Thus the motor is redesigned and developed with stator bore diameter increased from 105mm to 125mm. As per stator frame size, rotor slots changed from 33 to 28 as per standard. Instead of 96 conductors per slot of 24 SWG, 104 conductors per slot with 22 SWG conductors are used. And total number of turns is increased from 144 to 312. Insulation class is also changed from Class B (130° C) to Class F (155°C). These changes have reduced the stator resistance from 3.17 Ohms to 2.34 Ohms.

Stator Dimensions:-	
● **Stator Bore or Inner Diameter**	**125 mm**
● **Stator Slots**	**36**
● **Stack length**	**100 mm**
Rotor Dimensions:-	
● **Outer Diameter**	**125 mm**
● **Rotor Slots**	**28**
● **Stack length**	**100 mm**
● **Conductor size**	**22 SWG**
● **Conductors per slot**	**104**
● **No. of Turns per phase**	**312**
● **Insulation**	**Class F**

The winding layout as per new design is developed as shown below,

Figure 3.1 to figure 3.6 shows the complete winding of six phases.

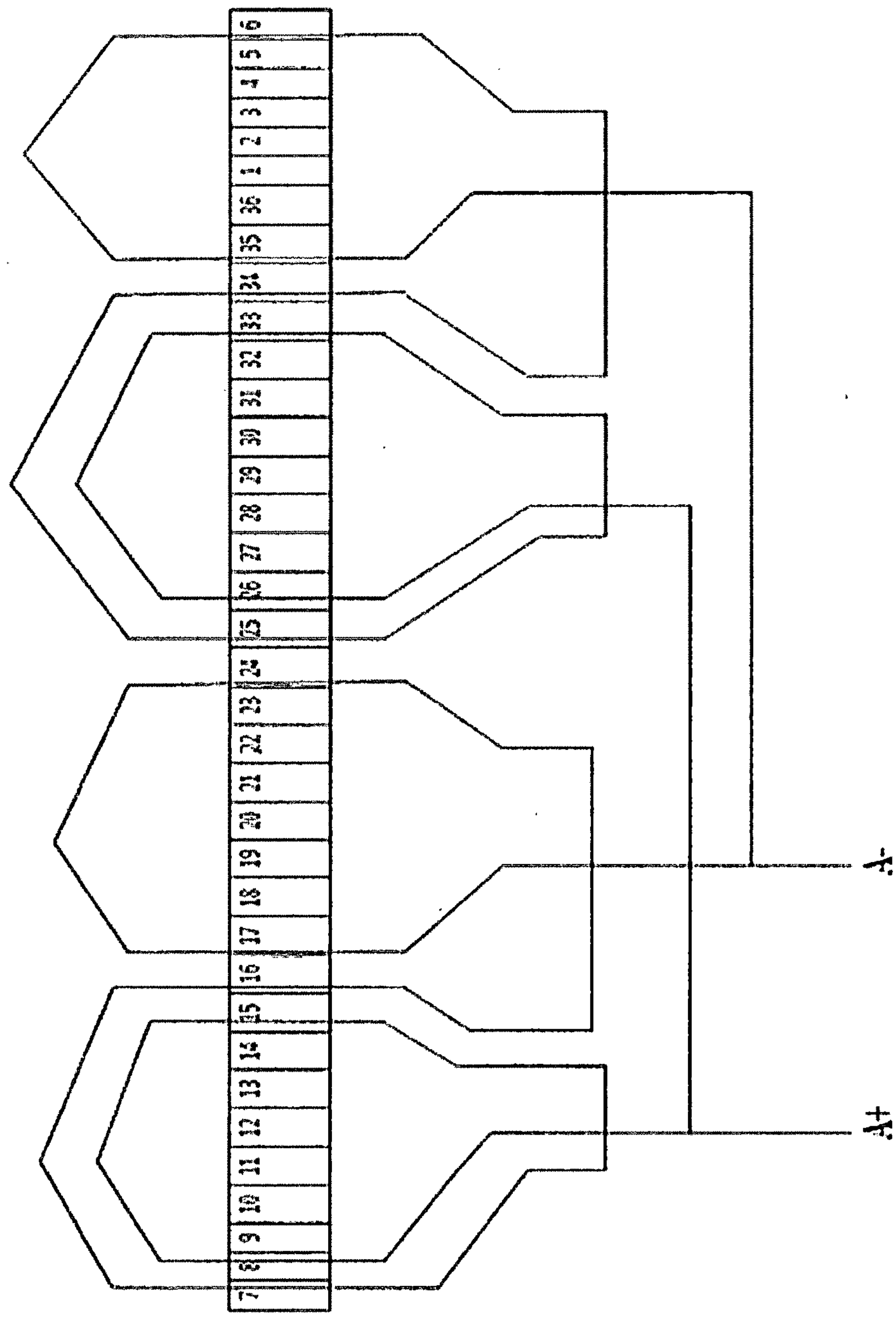


Figure 3.1 Winding Design of Phase A

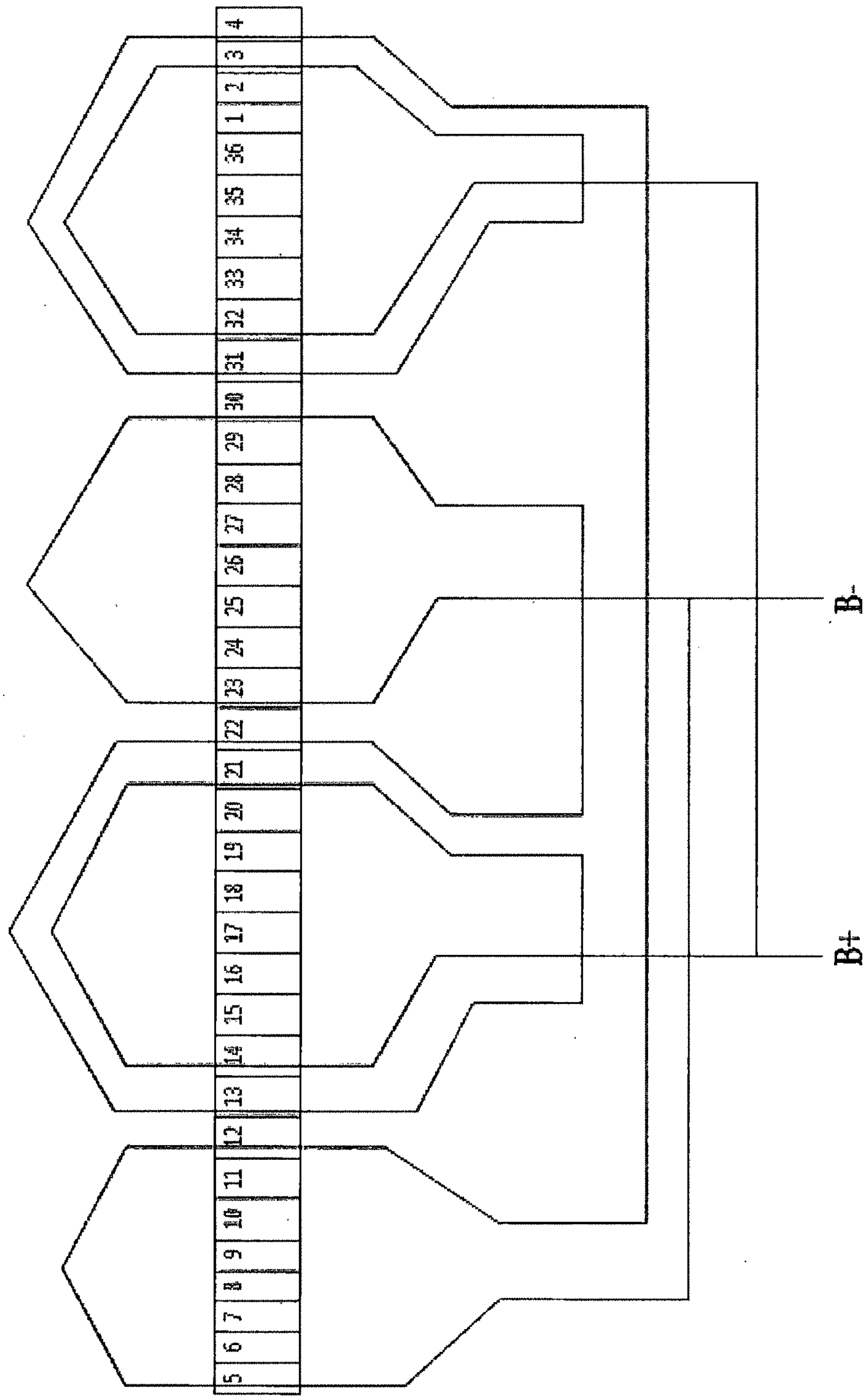


Figure 3.2 Winding Design of Phase B

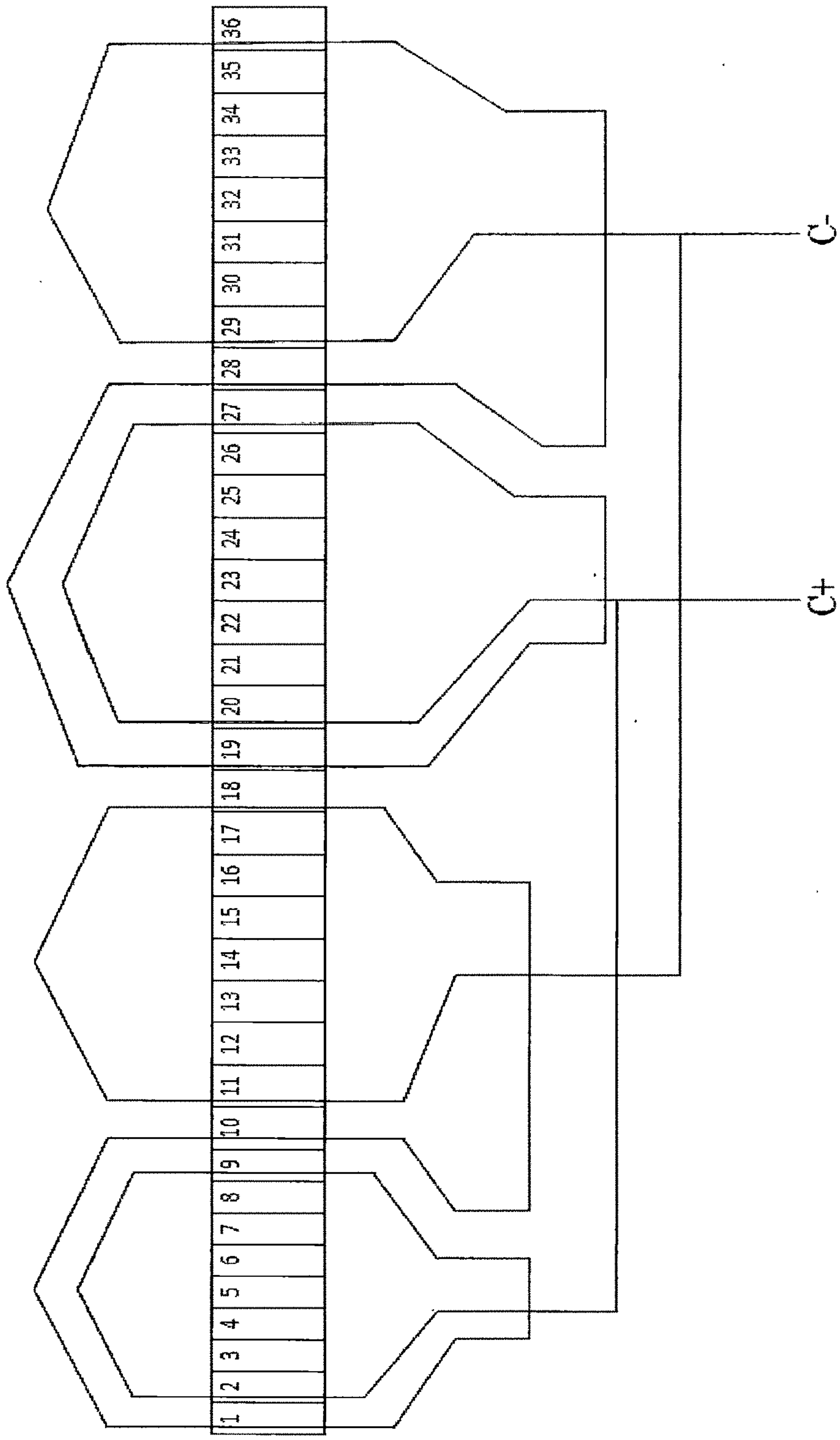


Figure 3.3 Winding Design of Phase C

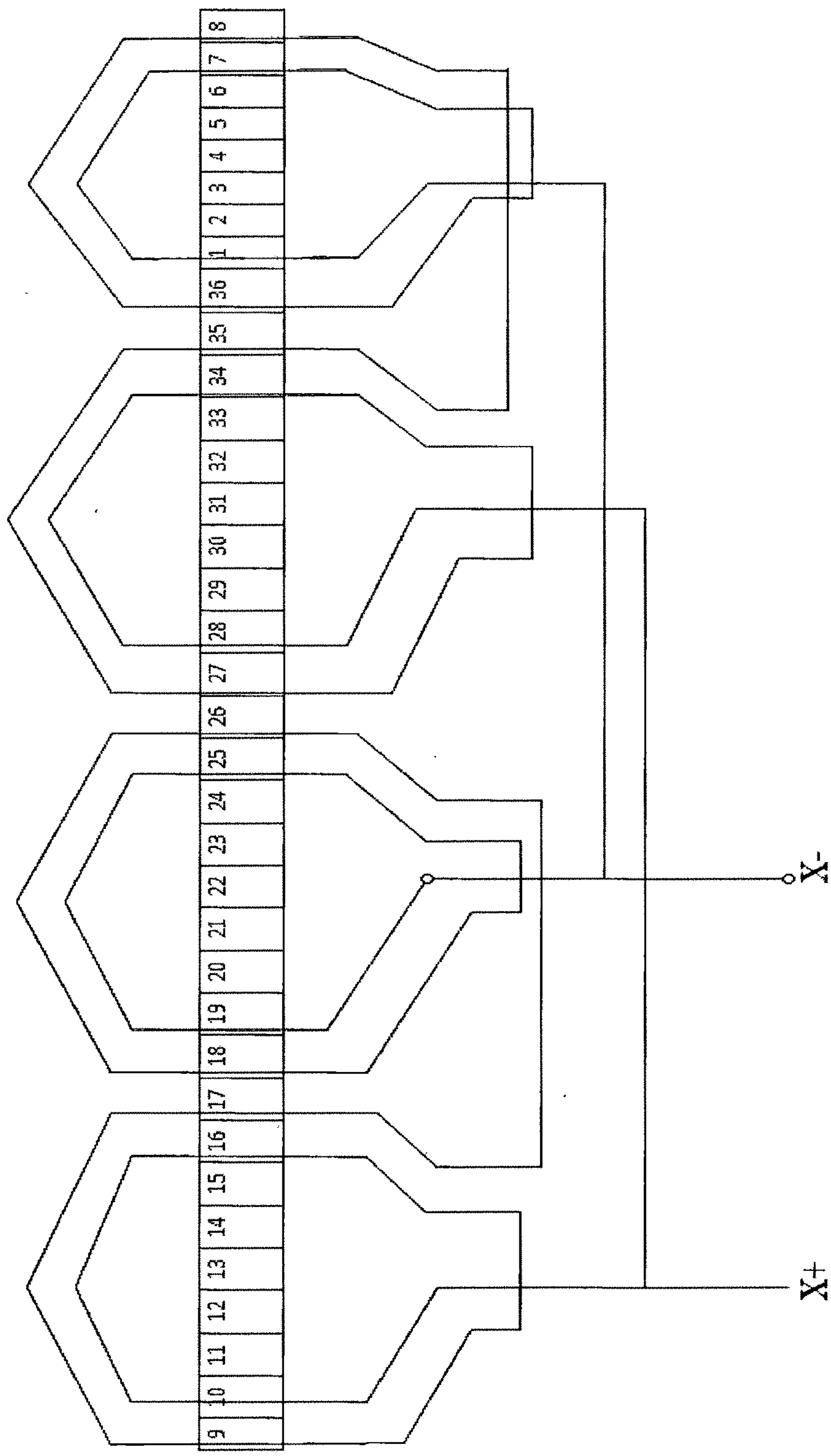


Figure 3.4 Winding Design of Phase X

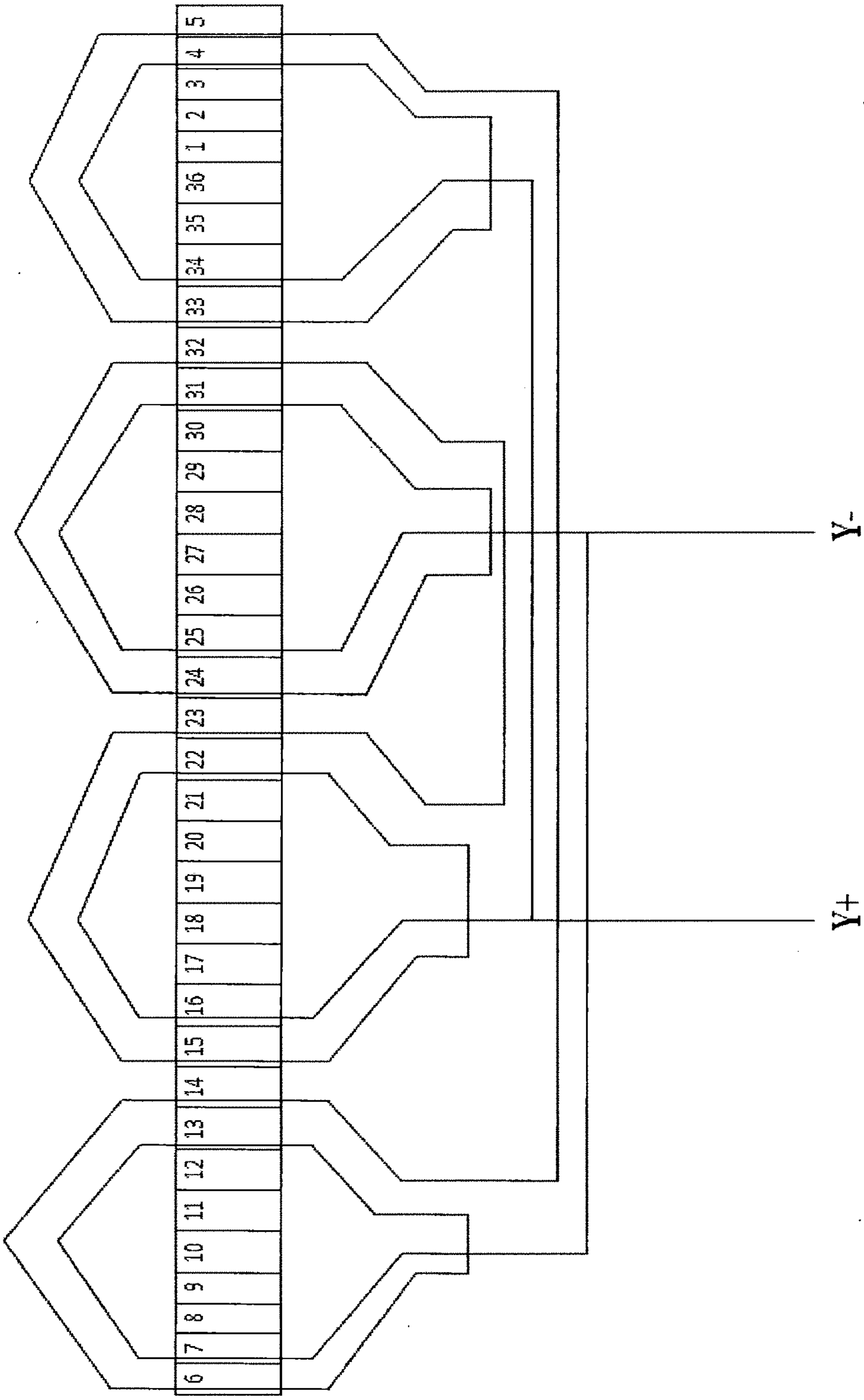


Figure 3.5 Winding Design of Phase Y

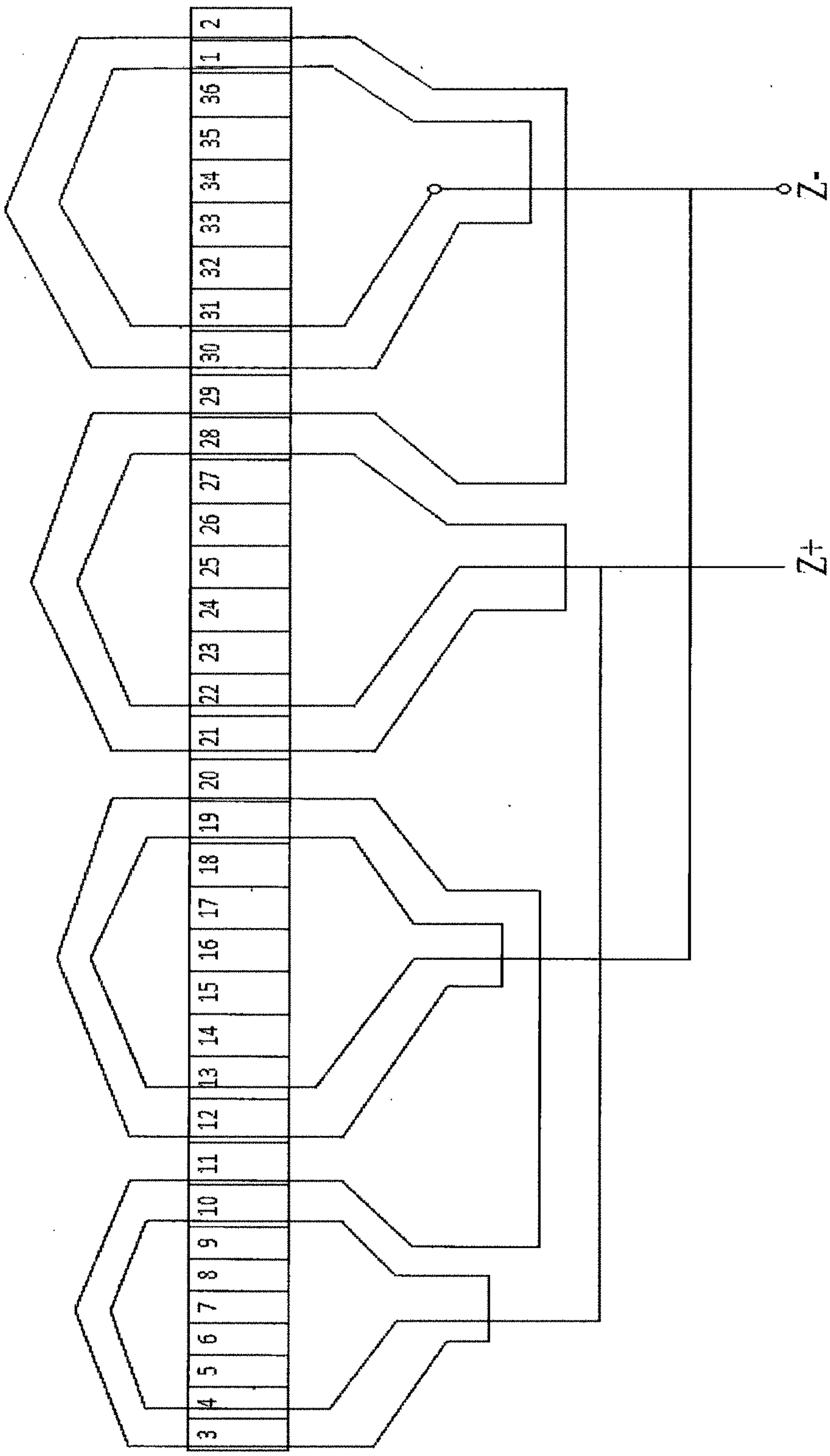


Figure 3.6 Winding Design of Phase Z

3.5 ACTUAL DEVELOPMENT OF PROTOTYPE SIX PHASE INDUCTION MOTOR

1. A stator lamination having diameter 125 mm is pressed into a cylindrical frame as per the stack length of 100 mm.

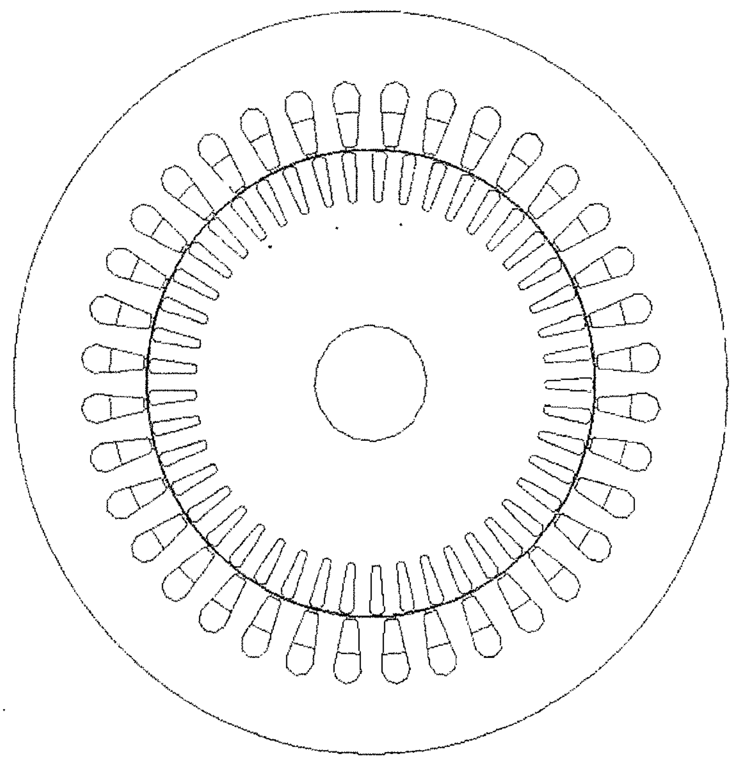
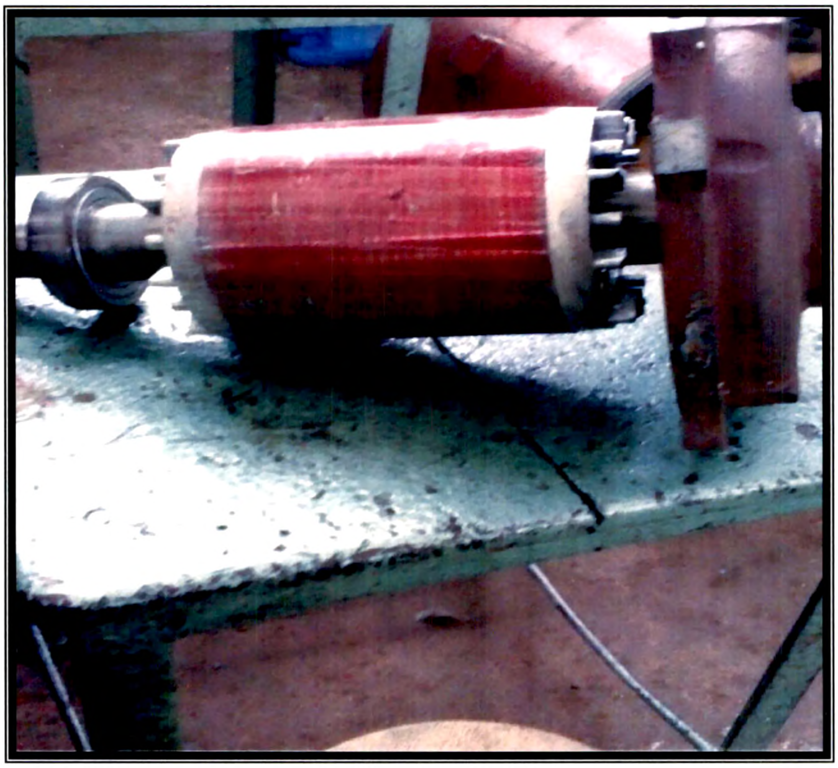


Figure 3.7 A stator lamination for 36 stator slots

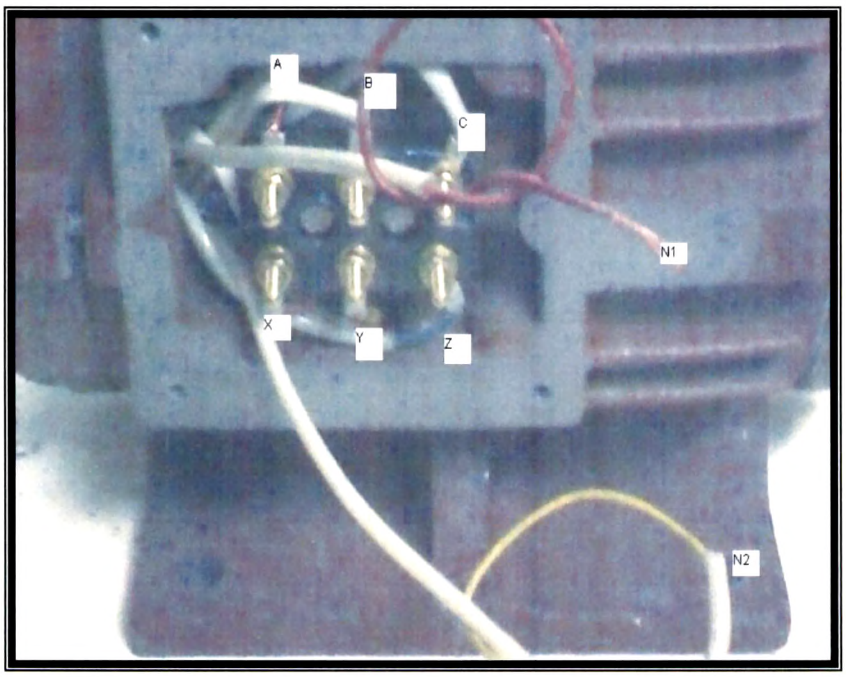
2. Rotor laminations as per the dimension are also pressed for 28 rotor slots.
3. Then windings are formed as per the number of turns per phase shown in the figure (3.1-3.6).
4. 22 SWG Copper conductors is used for winding.
5. Class F insulation is used.

Photograph 3.1. Actual winding

Photograph 3.2. Six phase stator after winding



Photograph 3.3. Rotor for prototype motor



Photograph 3.4. Prototype Six phase IM

3.6 TESTING

There is no standard separately for six phase induction motor. Thus the routine tests which are carried out for three phase motor , the same tests are carried out on prototype. It is considered like two, three phase induction motors sharing the same magnetic circuit and same shaft but electrically separated. Thus routine tests as per IS standards are carried out, by taking ABC and XYZ one by one.

A. HV Test:- A 2 KV voltage is given to the terminal box between phase to phase and phase to earth for one minute and there should be no sparking. If there is sparking, there may be inter turn fault.

Prototype six phase induction motor is tested like, two three phase stators sharing same shaft and same magnetic circuit and electrically separate. Prototype six phase induction motor satisfies this test, i.e. there is no sparking for both the three phase sets (ABC and XYZ).

B. Insulation Resistance (IR) Test: - Insulation resistance as per IS-325, should be 1 Mega Ohm.

Prototype six phase induction motor has insulation resistance 1MΩ for both three phase sets.

C. No load Test: - Motor is run at rated voltage at no load and rated speed. No load test results with waveform are shown below.

Supply Voltage	Current In Amp in ABC	Speed In RPM
60 V	**0.9**	**1475**
105 V	**1.27**	**1489**
152 V	**1.77**	**1491**
202 V	**2.33**	**1492**

Table 3.2 No load test results when ABC terminals energized

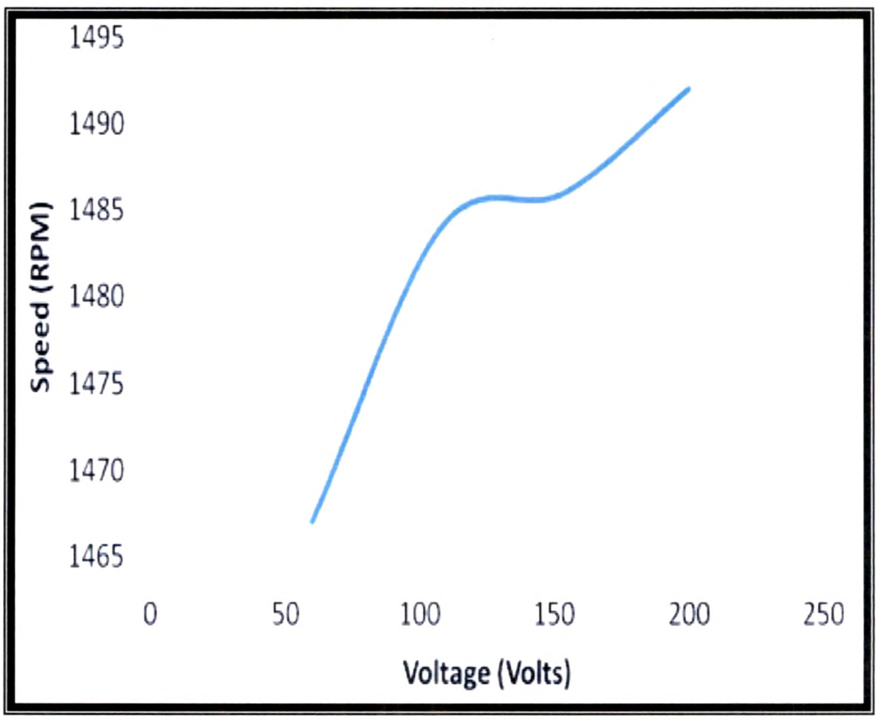


Figure 3.8 Speed Vs Voltage when ABC energized at No load

D. Blocked rotor test:- Full load current is passed when the rotor is locked. Test results are shown below

V_{sc} = 64 V, I_{sc} = 9.44 A

W_{sc} = 0.56 Kw

Speed N = 1460 rpm

E. Temperature rise Test:- Motor is run continuously for about a day and its temperature rise is noted, if it is getting overheated, winding and insulation is to be checked.

F. Load test:- Motor is loaded gradually at 50%, 75%, and 100%. Test results are shown below.

Photograph 3.5. Load test when ABC energized

Photograph 3.6. Load test when XYZ energized.

Supply Voltage	Current In Amp in XYZ	Speed In RPM
60 V	0.84	1467
108 V	1.36	1484
154 V	1.8	1486
200 V	2.38	1492

Table 3.3 No Load test results when XYZ Energized

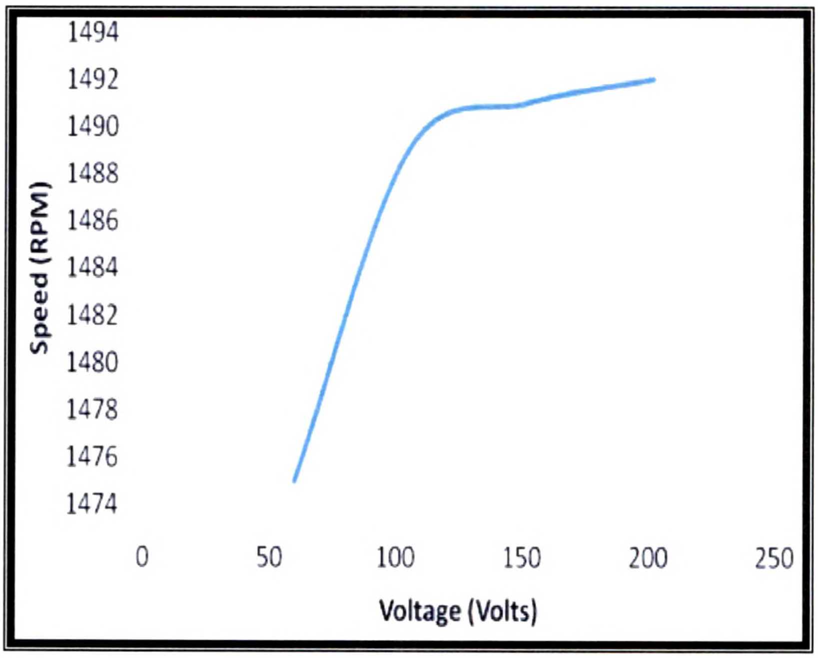


Figure 3.9 Speed Vs Voltage at No load when XYZ energized

Supply Voltage	Current in ABC (Amp)	Speed In RPM	Load in Kw
200 V	**3 Amp each**	**1460**	**0.78**
200 V	**3.5 Amp each**	**1450**	**1**
200V	**4.2 Amp each**	**1438**	**1.5**
200 V	**7.8 Amp each**	**1425**	**2.0**

Table 3.4 Load Test Results when ABC terminals energized

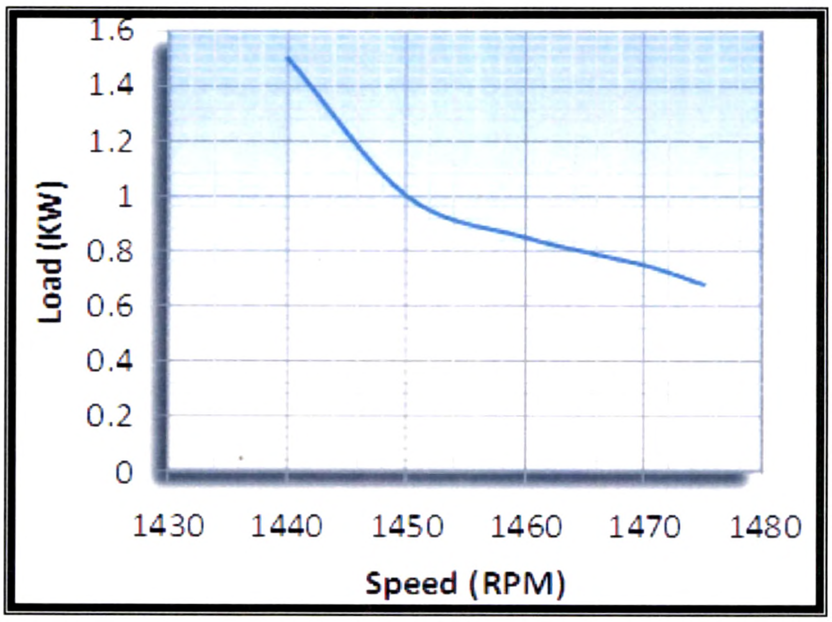


Figure 3.10 Speed Vs Load Characteristics when ABC terminals energized

Supply Voltage	**Current In Amp in XYZ**	**Speed In RPM**	**Load in Kw**
200 V	**2.95 Amp each**	**1468**	**0.72**
200 V	**3.46 Amp each**	**1452**	**1**
200V	**4. 1 Amp each**	**1438**	**1.5**
200 V	**7.5 Amp each**	**1425**	**2.0**

Table 3.5 Load test results when XYZ terminals energized

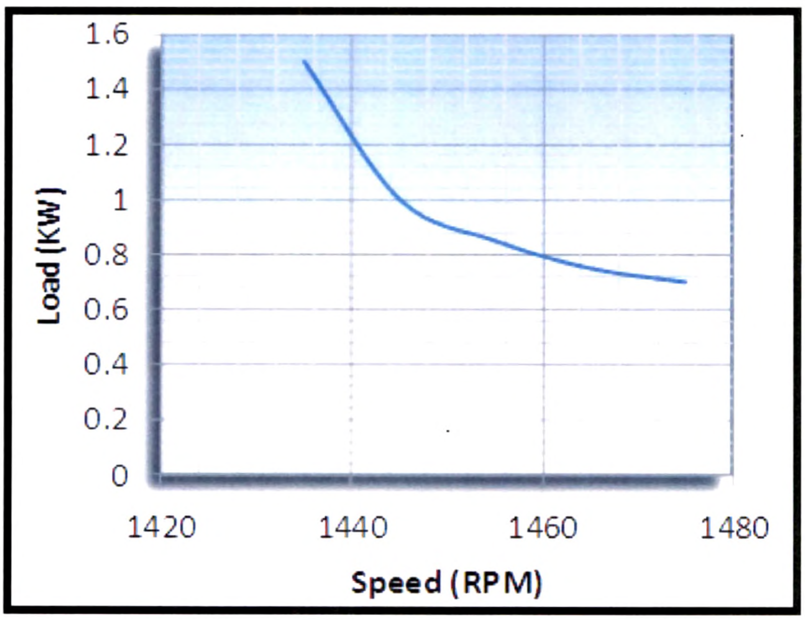


Figure 3.11 Speed Vs Load Characteristics when XYZ terminals energized

In no-load test, increasing voltage, increases the current and speed. While in load test, increasing current through load, reduces speed.

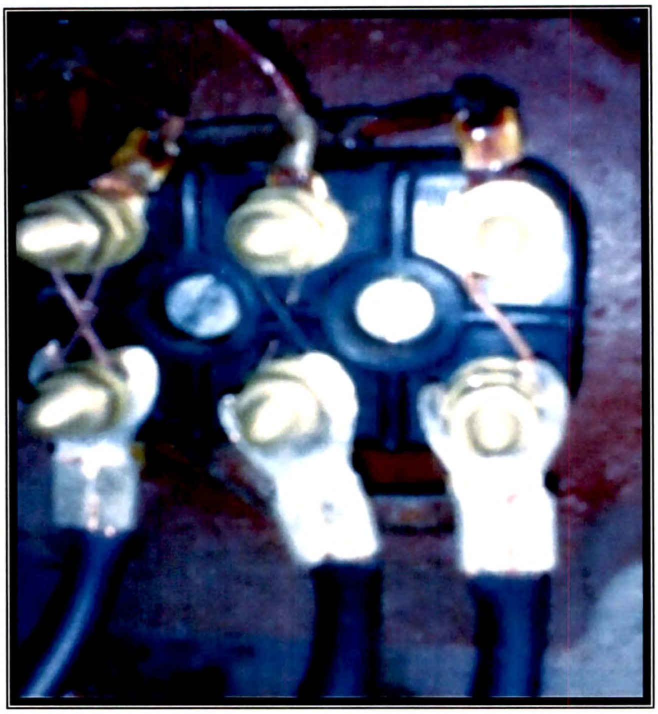
Apart from these tests, following tests are carried out as per customer requirement:-

G. Noise level test:- As per IS standards it should be less than 85 db. Prototype six phase induction motor satisfies this condition. Its noise level is below 85 db.

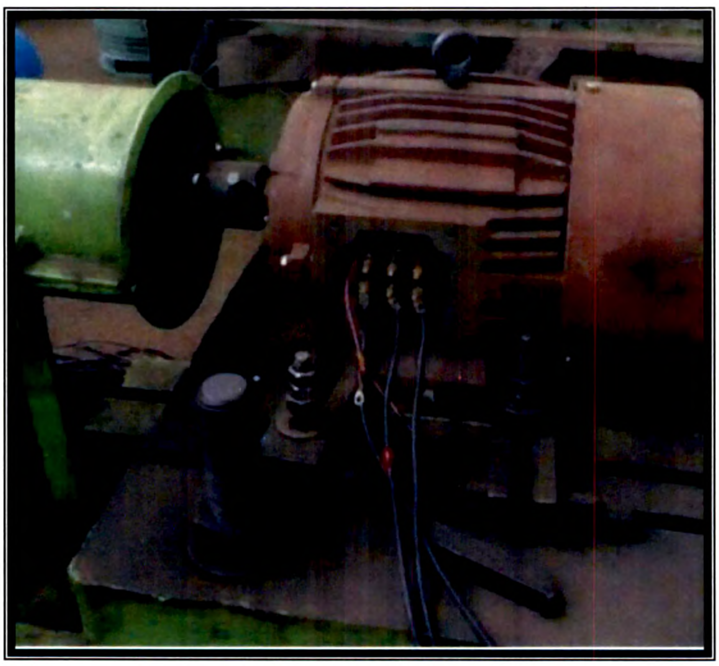
H. Vibration test:- Vibration should be minimum so as motor should not move. Prototype six phase induction motor vibration is minimum.

I. Momentary overload test:-Motor may be overloaded for 50% overload for few minutes. Prototype motor satisfies this test.

Before supplying the motor from two, three phase inverters, the no load and blocked rotor tests are carried out with two, three phase sets shorted. The six phase motor is supplied through three phase, 200 V, 50 Hz supply when A shorted to X, B to Y, C to Z. the same set up is supplied through single three phase inverter for variable frequency operation.



Photograph3.7 ABC terminals shorted to XYZ terminals respectively



Photograph 3.8 Testing with shorted terminals

No Load test results when ABC and XYZ shorted: (Six phase star connected 3 HP, 4 pole IM)

No Load voltage, V_0 = 200 V

No Load Current, I_0 = 4.19 A

No Load Speed N = 1475 rpm

No Load Loss W_0 = 0.36 Kw

In general,

$$W = mV_{ph} I_{ph} \text{Cos } \Phi \quad [3.18]$$

For three phase IM, m=3

$$W = 3\, V_{ph} I_{ph} \text{Cos } \Phi = \sqrt{3}\, V_L I_L \text{Cos } \Phi \quad [3.19]$$

For six phase IM, m= 6

$$W = 6\, V_{ph} I_{ph} \text{Cos } \Phi = 2\sqrt{3}\, V_L I_L \text{Cos } \Phi \quad [3.20]$$

$$W_0 = 2\sqrt{3}\, V_0 I_0 \text{Cos } \Phi_0 \quad [3.21]$$

$$\Phi_0 = W_0 / 2\sqrt{3}\, V_0 I_0 = 82.87^{\circ} \quad [3.22]$$

Blocked rotor test results

$V_{sc} = 64$ V

$I_{sc} = 9.44$ A

$W_{sc} = 0.56$ Kw

Speed N = 1460 rpm

$W_{sc} = 2\sqrt{3}\, V_{sc} I_{sc} \cos \Phi_{sc}$ [3.23]

$\Phi_{sc} = W_{sc} / \; 2\sqrt{3}\, V_{sc} I_{sc}$ [3.24]

$\Phi_{sc} = 74.47^{o}$

With this knowledge, the circle diagrams for three phase, 3 HP and six phase ,3 HP (shown in figure 3.19 and figure 3.20 respectively) are drawn to calculate torque and efficiency, etc. For three phase, 3 HP, 4 pole, 200V induction motor, choosing the scale of 1cm = 1 Amp the circle diagram as shown in the figure 3.19 is drawn. Power scale is 1 cm =340 Watt (Power scale: √3 x voltage)

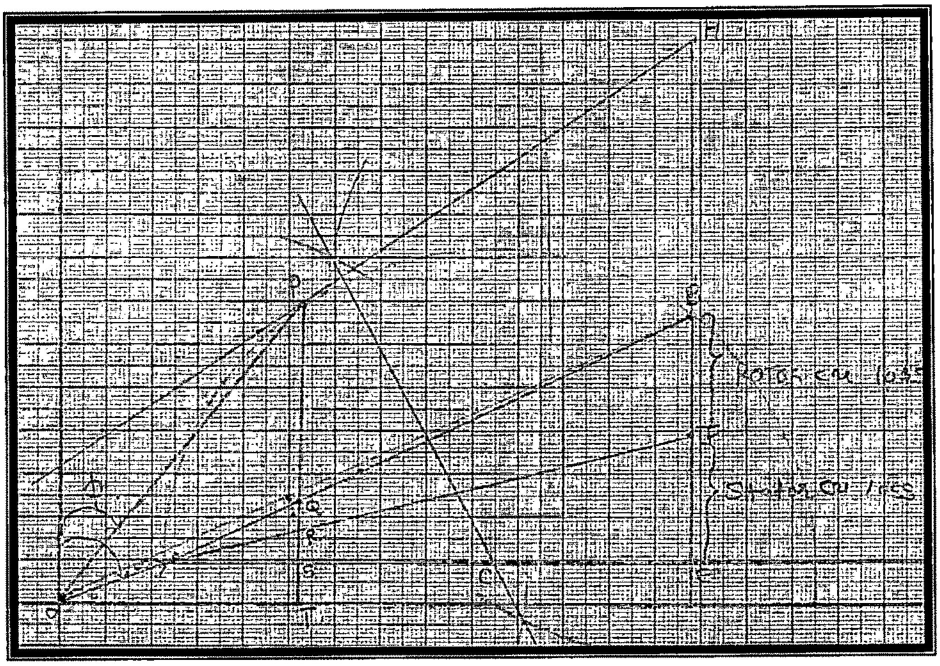


Figure 3.12 Circle diagram of three phase, 3 HP IM

From figure 3.12

Full Load line current OP = 8.4 cm

As per current scale, 1 cm = 1 Amp

Hence full load current = 8.4 Amp

Full load p.f. CosΦ = PT / OP = 6.8 / 8.4 = 0.8 lag [3.25]

Full load torque = Rotor input = PR = 5 cm

As per power scale 1 cm = 340 W

Hence full load torque = 5 x 340 = 1700 N-m [3.26]

Full Load Efficiency = PQ / PT = 4.5/6.8 = 66 % [3.27]

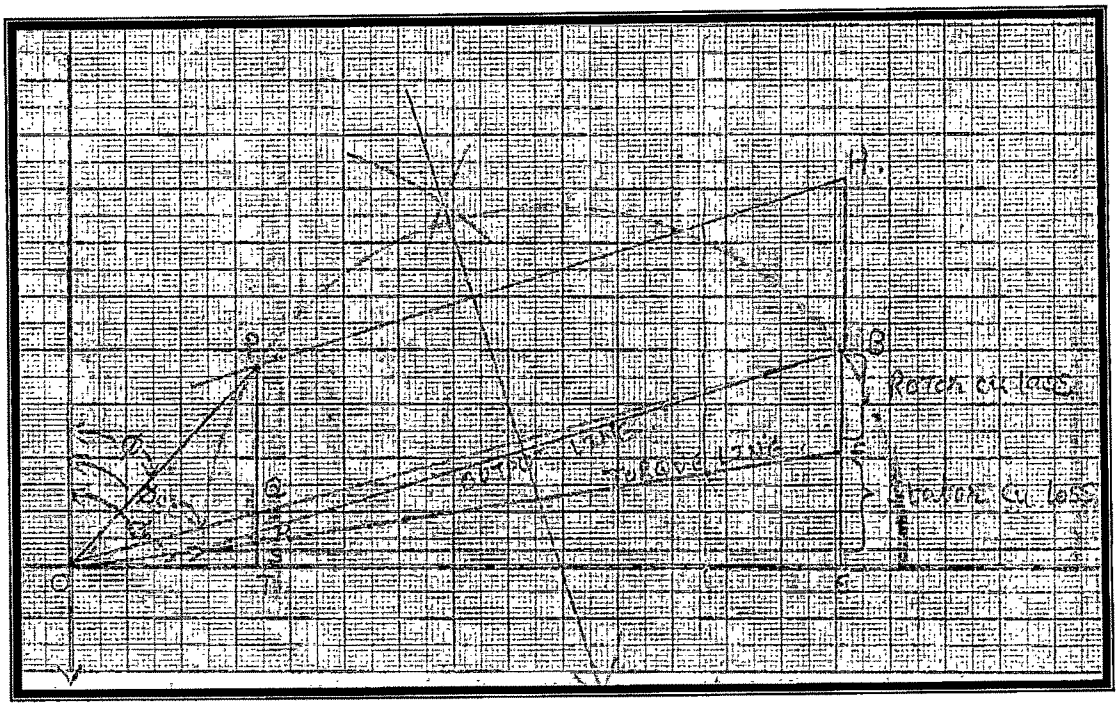


Figure 3.13 Circle Diagram of 6 phase 3 HP Motor

For six phase, 3 HP, 4 pole, 200 Volts Induction motor the current scale is

1 cm = 2 Amp and power scale is 1 cm = 695 W, (2√3 x voltage)

From figure 3.13,

Full Load line current OP = 5 cm

As per current scale 1 cm = 2 Amp

Hence Full load line current = 10 Amp

Full Load P.f. CosΦ = PT/ OP = 4/5 = 0.8 [3.28]

Full Load torque = Rotor input = PR = 3.9 cm [3.29]

As per power scale 1 cm = 695 W

Hence Full load torque = 3.9 x 695 = 2710.5 N-m [3.30]

Full Load Efficiency = PQ / PT = 3.5 / 4 = 88 % [3.31]

3.7 DISCUSSION:

From equations (3.26) and (3.30)

The full load torque of 3 HP, 4 pole, 200 volts, 3 phase induction motor is 1700 N-m and full load torque of 3 HP, 4 pole, 200 volts, 6 phase induction motor is 2710.5 N-m.

Thus

Full Load torque of 6 phase IM / Full Load torque of 3 phase IM

= 2710.5/1700 = 1.6.

Also efficiency of 6 phase IM = 88% ; From equation [3.31]

While efficiency of 3 phase IM = 66%; From equation [3.27]

From the circle diagram and calculations it is clear that the torque of six phase induction motor is more and found to be approximately 1.6 times more than equivalent three phase motor. Also Efficiency of six phase induction motor is 1.4 times more than that of equivalent three phase induction motor.

3.8 CONCLUSION

Three phase induction motor design and then six phase induction motor design, development and testing is discussed in detail in this chapter. Following points are noted:

1. The torque of six phase induction motor is much higher than equivalent three phase induction motor. Prototype six phase induction motor torque is 1.6 times that of equivalent three phase

motor. In [1]-[41] torque improvement is obtained by third harmonic current injection. Third harmonic current injection needs large inductors. The application of multiphase induction motor is mainly in high power-high current applications so the use of inductor for current injection is uneconomical. Though the initial cost of six phase induction motor is increased as compared to three phase induction motor but at the same time efficiency and torque are significantly improved. Also torque improvement with third harmonic current injection is 1.4 times that of equivalent three phase induction motor [1]-[41] while the developed prototype six phase induction motor torque is 1.6 times that of equivalent three phase induction motor. As the motor rating increases it is tedious to arrange third harmonic current injection externally and also uneconomical.

2. From the no load and load tests conducted separately on ABC and XYZ, it is obvious that the prototype motor is highly reliable: If one of the three phase sets is not supplied the motor will continue to run as three phase and continuity of operation is maintained as the neutrals are separate.
3. Instead of copper conductors, aluminum conductors may be used to reduce the cost, thus making it more economical.

4. When both the three phase sets will be supplied simultaneously through inverters may get better results.